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THE SOLAR CONTRIBUTION TO GLASSHOUSE HEATING

1. SUMMARY

Estimates of fuel based upon Morris' formula (5) have been made for tomato growers in the South West Region but these estimates have been in error by up to 50% for a complete growing season. Data from an NIAE* experiment have been used to develop a computer model to calculate fuel use. It takes into account solar radiation and the contribution from CO_2 production as well as ambient temperature and windspeed. The model has enabled estimates of the ground heat flux to be made and better calculations of daytime heat loss (transmission) coefficients. It could be run with climatological data to calculate the long term economic effects of various temperature regimes.

The model solves the following heat balance equation for each hour:-

$$U.T_1 + G + P = \beta.R + C + F$$

U	=	the heat loss coefficient	$\beta.R$	=	solar contribution
T_1	=	temperature lift	C	=	heat released by CO_2 production
G	=	ground heat flux			
P	=	purging loss; at dusk only	F	=	energy supplied by heating system

2. INTRODUCTION

During February and March 1979 NIAE measured heat losses in a widespan glasshouse at Eric Walls nursery in West Sussex and related them to mean temperature lift and windspeed (2) (Bailey, 1979). The glasshouse was 22.3 m wide, 100.5 m long, 3.4 m to the eaves, 8.8 m to the ridge and was orientated east-west. Windspeed was measured at 12 m AGL and heat consumption was determined using a Carlton flow meter.

Bailey obtained a good fit of night-time transmission coefficients with the regression line:-

$$U = 5.25 + 0.375\ W \qquad - 1$$

Where U is the transmission coefficient ($W\ m^{-2}K^{-1}$) and W is the windspeed (ms^{-1}). This compares with Morris' equation (also based on night-time losses) of:-

$$U = 4.25 + 0.63\ W \qquad - 2$$

Both formulae give a heat loss coefficient of 6.7 $W\ m^{-2}\ K^{-1}$ at a windspeed of 3.6 ms^{-1} though it is not clear at what height Morris measured the windspeed. Using measured heat losses, from the hot water circulation system only, daytime transmission coefficients show a good deal of scatter

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about the best fit line:-

$$U = 3.63 + 0.25\ W$$

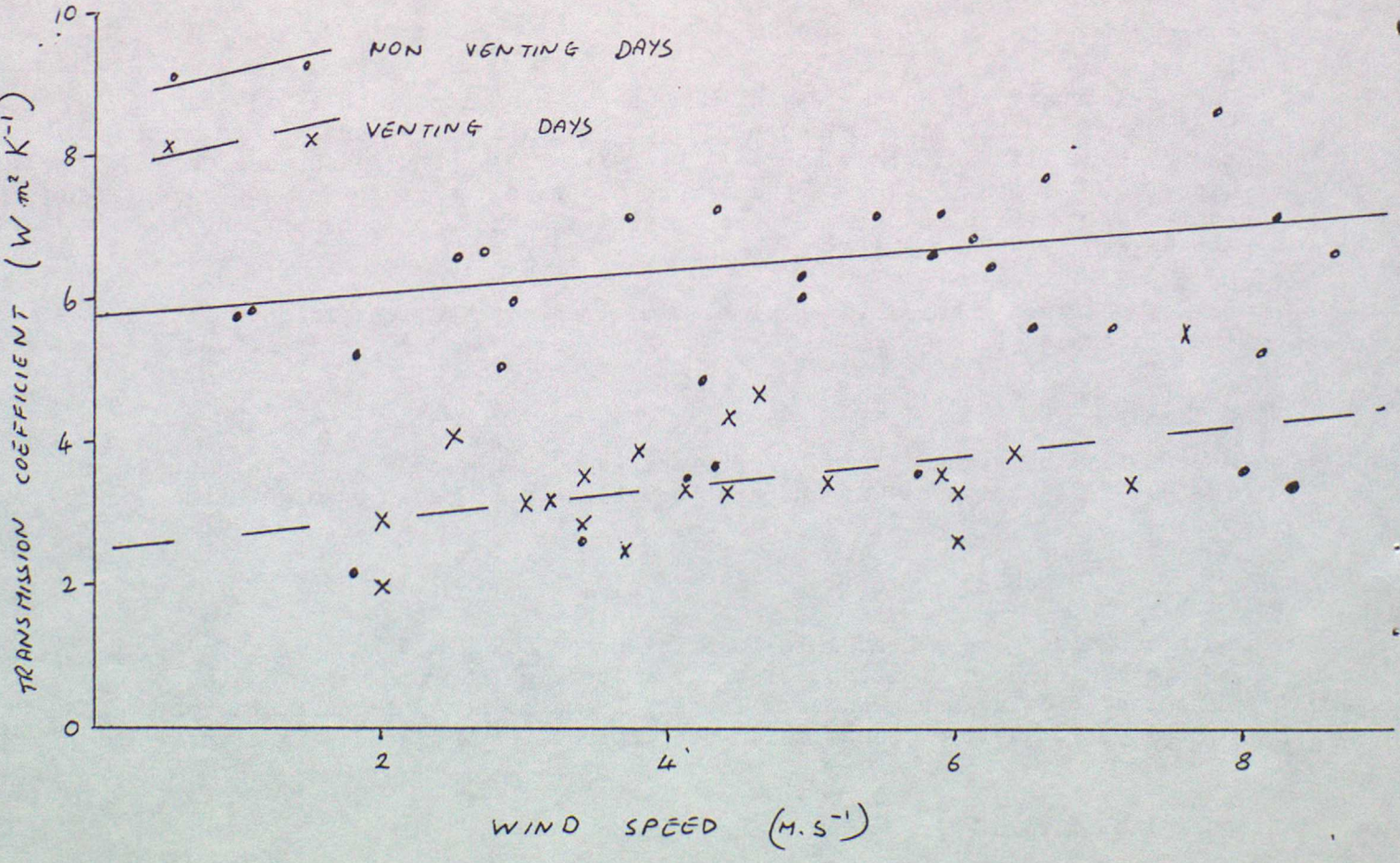
When heat losses have been normalised for temperature lift there should be no significant difference between day and night values. This difference in transmission coefficients is attributed to neglecting the solar energy input and that derived from CO_2 production. Figure 1 shows the uncorrected daytime transmission coefficients plotted against windspeed. Venting and non venting days (see section 4) tend to fall into 2 separate groups. These data are summarised below:

TABLE 1

UNCORRECTED TRANSMISSION COEFFICIENTS ($U = a_o + a_1 W$)

	REGRESSION COEFFICIENTS a_o	a_1	CORRELATION COEFFICIENT r	NUMBER OF CASES n	SIGNIFICANCE LEVEL OF r	STANDARD ERROR
Venting Days	2.45	0.235	0.480	21	3%	0.68
Non Venting Days	4.87	0.165	0.227	32	NOT SIG	1.554
All Days	3.63	0.250	0.290	53	5%	1.639

FIG 1. UNCORRECTED HEAT LOSS COEFFICIENTS



3. THE SOLAR CONTRIBUTION

a. Estimating radiation

Daily radiation at the site was estimated from Efford's readings by the method described below. Some days data were excluded from the analysis because the weather at Herstmonceux and Hurn was considered to be such that reliable estimates were impossible.

If G_{OE} = global radiation at Efford
I_E = direct radiation at Efford
n_E = sunshine at Hurn (representative of Efford)
n_H = sunshine at Herstmonceux (representative of the glasshouse site)
N = day length
$I_E = 0.5\, G_{OE}\, n_e/N$ (3)

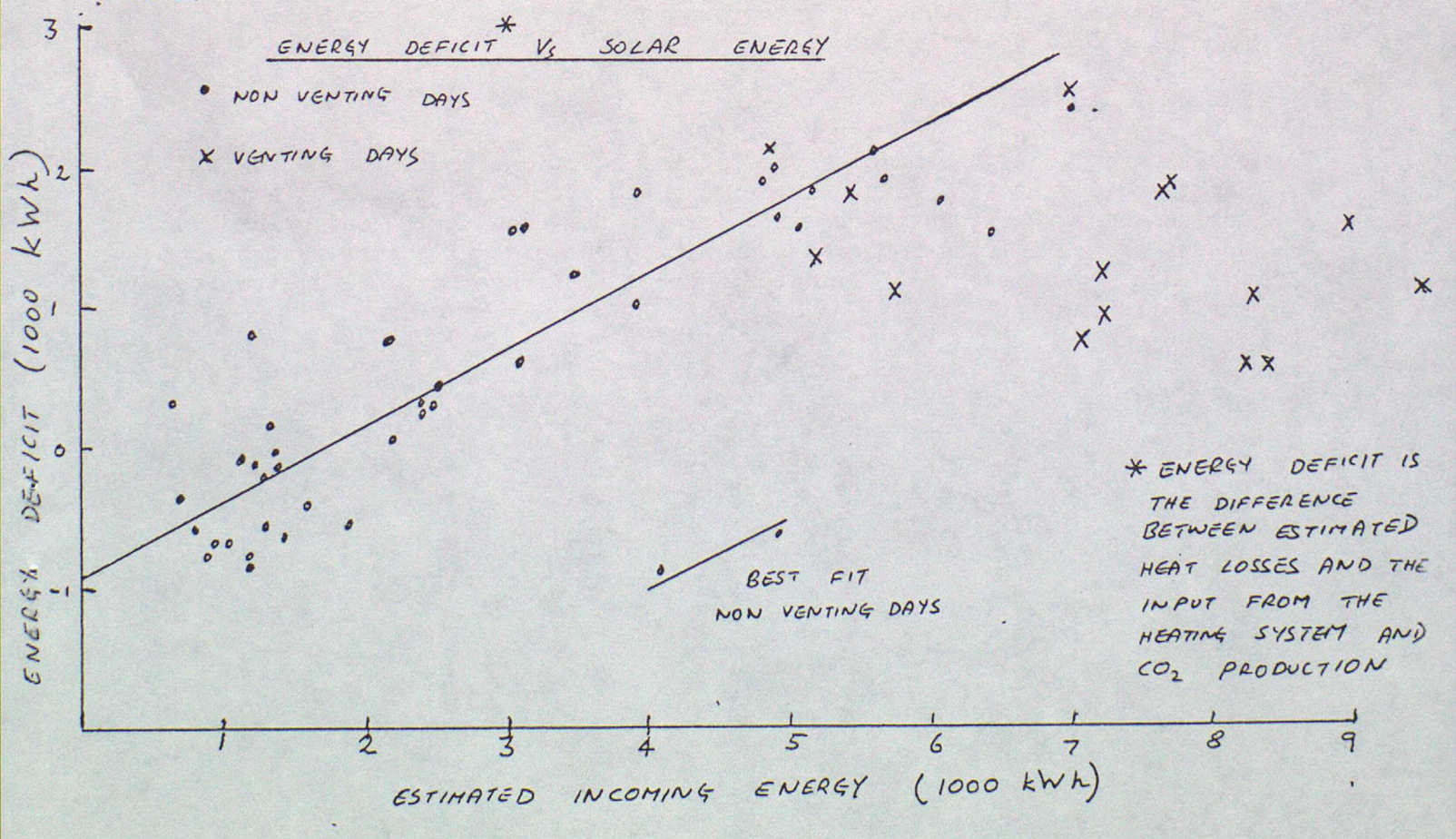
Diffuse radiation is assumed to be the same at both sites = $G_{OE} - I_E$. It is also assumed that the ratio between direct radiation at the glasshouse site and that at Efford is given by n_H/n_E.

Thus total radiation at site = $(G_{OE} - I_E) + I_E\, n_H/n_E$ - 4

b. Ground heat flux

Daytime heat losses were calculated from mean windspeeds and temperature lifts using equation 1. Duration of CO_2 production was deduced by running the model iteratively which also identified venting days. (See section 4.) Differences between measured and calculated heat losses were plotted against total radiation. See figure 2.

FIG 2.



It can be seen that for days with fairly high radiation (>5000 kWh) the ratio between radiation used and incoming radiation falls. The lower ratio occurs on venting days. The regression line through the non-venting points is:

$$\text{Radiation used} = 0.544\ \text{EIR} - 975\ \text{(kWh)} \qquad - 5$$

Where EIR = estimated incoming radiation.

This implies a maximum radiation utilisation factor (RUF) of 54.4% and this was subsequently used in the model. The intercept of - 975 kWh for the line drawn through the non-venting points in figure 2 implies that during the average non-venting day 975 kWh more energy was put into the glasshouse then was calculated as necessary using equation 1. If it is assumed that additional heat is used to raise the mean temperature of the soil and structure from their night value to their day value then the same quantity of heat must flow out of the soil and the structure when the temperature drops at night. No account was taken of such heat flow when equation 1 was deduced and so it underestimates the heat transmission coefficient of the glasshouse. It has been assumed that half of the extra 975 kWh of energy put into the house on non-venting days was stored in the soil and the structure and the other half represents an underestimate of transmission losses. For the non-venting days during the experimental period the average diurnal difference in internal temperature was $3.5^{\circ}C$ and average day length 10.5 hours. This is equivalent to a mean flux of 5.9 W m^{-2} K^{-1} for the glasshouse covering 2241 m^2. A source of 487 kWh of heat would thus increase the night heat loss coefficient by 0.83 wm^{-2} K^{-1} since the average temperature lift was $12.6^{\circ}C$, night length 13.5 hours and area of glass was 3446 m^2

$$\text{giving } U = 6.14 + 0.375\ W \qquad - 6$$

These results have been incorporated in the model. See sections 4a (II) and 4b (II).

4. THE HEAT BALANCE MODEL

By assuming that transmission coefficient equations are the same for both night and day it is possible to write a computer model to evaluate the various energy components required for the heat balance. Heat gains and losses are calculated for each hour with night and day summaries produced for each 24 hour period. Times of sunrise and sunset are calculated from the following (7)

Let d = day of year (1 Jan = 1)
δ = solar declination
ϕ = latitude
t_1 = time of sunrise
t_2 = time of sunset

Then
$$\delta = 23.5 \cos 2\pi \frac{(d - 173)}{365} \text{ in degrees}$$

$$t_1 \simeq \frac{12}{\pi} \arccos(\tan\delta \cdot \tan\phi) \qquad - 7$$

$$t_2 \simeq 24 - t_1 \qquad - 8$$

and day length = $t_2 - t_1$ $\qquad - 9$

4a. HEAT LOSSES

I. Transmission

Transmission losses are evaluated using Bailey's equation modified for the ground heat flux correction - equation 6. Mean windspeeds and internal temperatures used in the analysis were those measured on site but provision has been made for a wind correction factor to be used to modify wind speeds measured at a nearby recording station. Outside air maximum and minimum temperatures also form part of the input data. For the NIAE experiment maxima and minima were deduced from day and night mean temperatures. Air temperature is assumed to follow a cosine curve between the minimum at 0600 GMT and the maximum at 1400 GMT and again to the following day's minimum at 0600 GMT.

II. Ground heat flux

Daily heat input to the ground and structure is taken as 0.062 kWh m^{-2} for each degree temperature rise from the night to day regime. The hourly heat flux is given by G = DAILY FLUX/2^n where n is the number of hours since sunrise.

III. Purging

When fuel is burnt to produce CO_2 it is common practice to purge the glasshouse at the end of the day and the model assumes one complete airchange to achieve this. It calculates the energy required to raise a volume of air equivalent to that of the glasshouse from the outside air temperature at sunset to the night-time target temperature. On average this was less than 40 kWh and because of the uncertainty of the purging procedure or the number of air changes which could be expected (see reference 8 for example) this was ignored in calculating the transmission coefficients. If included the effect is to decrease the transmission coefficients by about 1% for each air change.

4b HEAT GAINS

I. Solar gain

Hourly irradiance is estimated by integrating the irradiation curve which follows a cosine curve between sunrise and sunset with a maximum at 1200 GMT. A radiation utilisation factor (RUF) controls the fraction of irradiation used for heating. The model has been run with $0.1 < RUF < 0.75$. Radiation contributes to the energy requirement when the target temperature exceeds outside air temperature but only that amount required to balance the losses is counted in the daily summaries.

II. Soil heat flux

From figure 2 and section 3b it has been deduced that the heat stored

by the ground and structure is equivalent to 487 kWh for an average internal diurnal variation of 3.5°C and ground area 2241 m^2. This gives a total night flux of 0.062 kWh m^{-2} with hourly values given by G = NIGHT FLUX/2^n where n is the number of hours since sunset.

III. CO_2 production

It is common practice to burn hydrocarbon fuel during the day to generate carbon dioxide. For want of better criteria the model assumes that fuel is burnt during daylight hours when transmission and ground heat flux losses exceed the solar input. Fuel is burnt at a rate that produces 55 kg h^{-1}/ha of CO_2 according to table 2.

TABLE 2

FUEL	RATE OF BURNING kg/h/ha	NET CALORIFIC VALUE MJ/kg	ENERGY PRODUCED kWh/h/ha
Propane	19.0	46.2	243.8
Paraffin	18.1	34.5	173.5

Gross calorific values include energy recoverable from the latent heat of vaporisation of water in the fuel and are about 7% greater than net calorific values. It is thought firstly that most of this water vapour will be lost from the glasshouse and secondly that fuel burnt is being overestimated and so net values are used. The fuel burners are usually controlled by the vents opening which operate a few degrees above target temperature but the model only sums contributions from CO_2 production at and below target temperature. A day is classified as a VENTING DAY when calculated heat generated by CO_2 production is less than the amount which would have been produced for all daylight hours. Venting days were assessed using a RUF of 40%.

Model results for a typical sunny day are shown in Appendix III. Areas enclosed by the graphs are proportional to to individual energy contributions.

5. RESULTS AND DISCUSSION

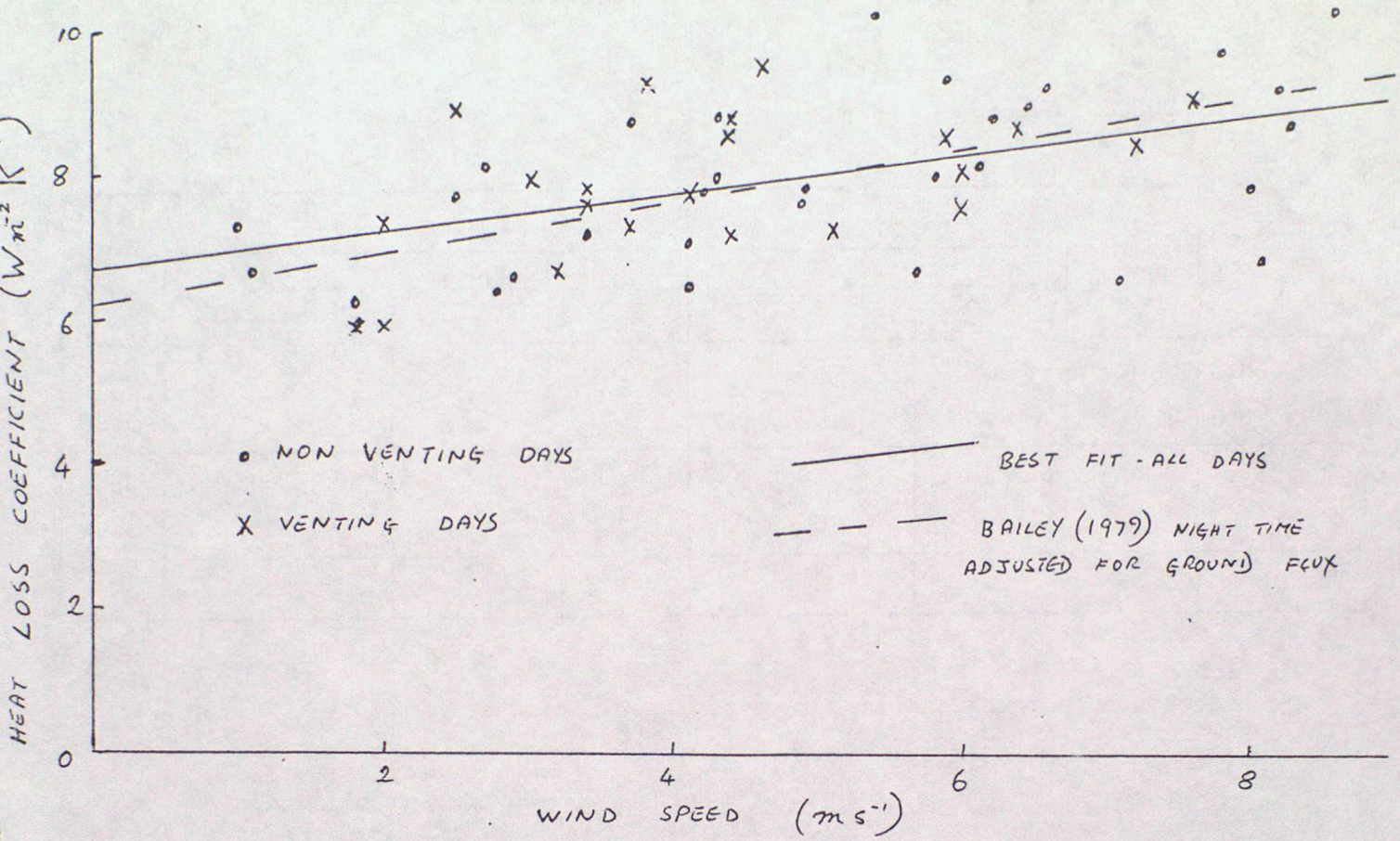
a. Contributions from CO_2 production and from irradiation were evaluated using the model. These were combined with the daily heating system losses and an estimate for ground heat flux to calculate transmission coefficients. The coefficients are plotted against windspeed in figure 3, venting and non-venting days have been shown as in figure 1. These data are summarised for the 2 month period in table 3.

TABLE 3

CORRECTED TRANSMISSION COEFFICIENTS ($U = a_o + a_1 W$)

	REGRESSION COEFFICIENTS a_o	a_1	CORRELATION COEFFICIENT r	NUMBER OF CASES n	SIGNIFICANCE LEVEL OF r	STANDARD ERROR
Venting Days	6.88	0.261	0.450	21	5%	0.80
Non Venting Days	6.47	0.291	0.557	32	1%	0.956
All Days	6.66	0.275	0.516	53	0.1%	0.908

FIG 3. CORRECTED HEAT LOSS COEFFICIENTS



It is to be expected that the regression line for all days is similar to the modified Bailey night-time regression line (equation 6) since this was used to estimate the solar gain. The standard error for venting days is smaller than that for non venting days which is probably due to the poor radiation estimates for wet days which contribute most to the scatter. However the reduction in the standard error for 'all days' from 1.639 for the uncorrected losses to 0.908 for corrected losses is most encouraging. An F test shows this to be significant at the 0.1% level and gives some confidence in the model.

b. Ground and structural heat storage was estimated to be 0.062 kWh $m^{-2}K^{-1}$.

c. Solar heat gain was estimated at 54.4% of total radiation when the vents are closed which is very high compared with previous estimates and is over 80% of the estimated radiation entering the glasshouse. Forsdyke [4] apportions incoming energy as 70% for evaporation and 30% for sensible heating. His estimates are in good agreement with Rothwell and Jones [6] who measured water uptake by a tomato crop and found it to be equivalent to about 65% of incoming radiation for full cover. A value over 80% of net radiation used for heating therefore suggests that much of the energy used for transpiration is recovered A lower leakage rate for the modern glasshouse suggested by the slope of the regression lines (0.275, 0.375) compared with Morris' value (0.63) adds some weight to this argument. (1)

d. From appendices I and II the mean heat balance for the period of the experiment was calculated and the results tabulated below.

TABLE 4

WALLS GLASSHOUSE FEB/MARCH 1979

	% LOSSES			% GAINS			
	GROUND FLUX	PURGING	TRANSMISSION	GROUND FLUX	CO_2 BURNING	SOLAR CONTRIBUTION	FUEL
Non Vent	10.2	1.1	88.7	0.0	11.5	23.9	64.6
Vent	9.5	0.5	90.0	0.0	5.5	55.7	38.7
All Days	9.9	0.8	89.3	0.0	9.0	37.1	53.9
Night	0.0	0.0	100.0	11.6	0.0	0.0	88.4
Total	5.3	0.5	94.2	5.3	4.9	20.0	69.8

Any comments or suggestions on this paper should be referred to the author.

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APPENDIX I. NON VENTING DAYS - (BASED ON 40% RUF)
1979 DATA FROM HEAT BALANCE MODEL FOR WALLS GLASSHOUSE

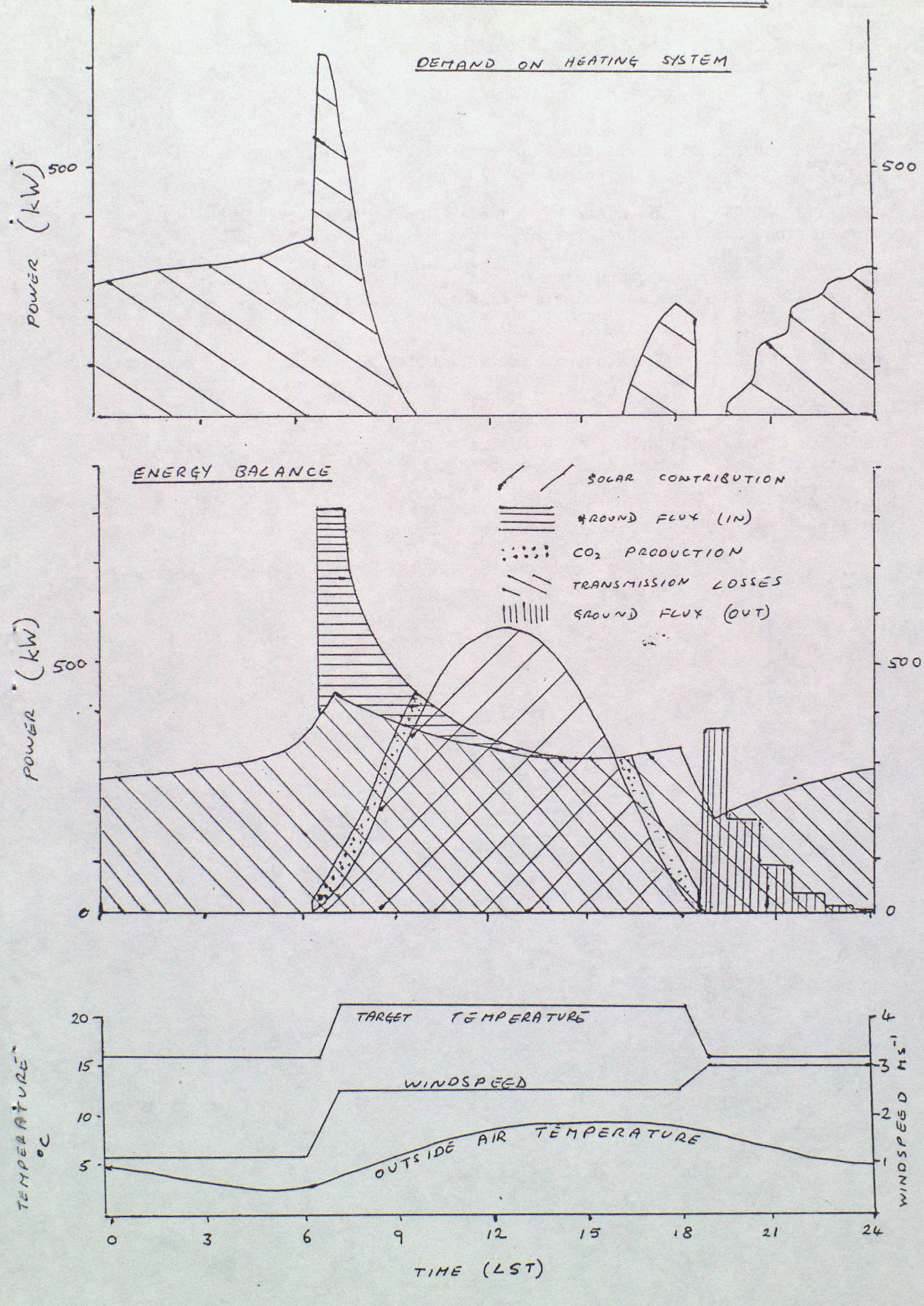
DATE	MEASURED CONSUMPTION kWh	CO_2 ENRICHMENT kWh	(SOLAR CONTRIBUTION - 487) kWh	PURGING LOSSES kWh	TEMPERATURE LIFT °C	TRANSMISSION COEFFICIENT $W\ m^{-2}K^{-1}$	WIND SPEED ms^{-1}
1/2	2209	487	- 145	44	12.2	6.6	7.1
2/2	1975	485	1397	33	17.2	7.1	3.6
3/2	1731	320	2539	61	19.9	7.2	3.4
4/2	2847	495	268	51	14.5	7.8	4.9
5/2	2347	498	879	32	14.8	7.8	4.2
6/2	3650	501	192	38	16.1	8.2	6.9
8/2	3439	508	709	59	15.9	8.9	6.2
9/2	3370	511	187	48	15.3	8.0	5.8
10/2	4034	514	- 1	59	13.9	9.8	7.8
11/2	4045	517	201	57	15.4	9.3	6.6
12/2	3278	520	277	37	16.6	7.3	1.0
13/2	2603	523	63	30	10.5	8.9	4.3
14/2	3545	527	815	55	15.3	9.4	8.6
15/2	2011	530	1189	69	16.1	6.7	5.7
16/2	3778	533	254	71	17.0	7.7	4.9
17/2	3906	537	- 137	78	18.7	6.6	2.9
18/2	3939	540	22	75	19.0	6.7	1.1
19/2	3231	543	135	64	17.6	6.3	1.8
20/2	2997	547	239	51	16.6	6.4	2.8
21/2	3906	550	147	55	16.5	7.8	2.5
26/2	1545	450	2159	47	19.0	5.9	1.8
2/3	1603	581	661	31	11.7	6.5	4.1
10/3	4603	610	387	78	16.2	8.8	3.7
11/3	2428	613	831	23	10.9	9.0	6.5
13/3	3567	621	147	36	13.4	8.1	2.7
14/3	4509	624	- 58	53	13.5	9.3	8.2
15/3	2639	627	140	58	12.1	6.9	8.1
16/3	5000	631	1450	61	16.9	10.3	5.4
19/3	4023	642	525	49	13.4	9.4	5.9
24/3	2045	660	1658	49	12.9	7.9	8.0
26/3	1847	667	2133	41	12.3	8.8	8.3
29/3	2231	678	1653	43	13.1	8.0	4.3

APPENDIX II. VENTING DAYS - (BASED ON 40% RUF)
1979 DATA FROM HEAT BALANCE MODEL FOR WALLS GLASSHOUSE

DATE	MEASURED CONSUMPTION kWh	CO_2 ENRICHMENT kWh	SOLAR CONTRIBUTION - 487 kWh	PURGING LOSSES kWh	TEMPERATURE LIFT °C	TRANSMISSION COEFFICIENT $W\ m^{-2}K^{-1}$	WIND SPEED ms^{-1}
24/2	2220	372	2225	26	18.5	7.2	4.4
25/2	1453	270	2625	23	20.3	5.9	2.0
27/2	1825	352	2699	50	17.3	7.6	3.4
28/2	2045	376	1878	21	15.9	7.3	5.1
1/3	1928	318	2768	52	15.5	8.6	4.4
4/3	1661	166	1679	0	13.6	6.7	3.2
5/3	2314	175	2597	33	14.9	8.9	2.5
6/3	1895	386	2393	37	14.9	8.1	6.0
7/3	2417	216	2214	19	14.2	8.8	4.4
8/3	2150	272	2786	52	14.3	9.3	3.8
9/3	2672	449	1193	12	12.1	9.1	7.6
12/3	1453	356	2387	29	13.9	7.6	6.0
17/3	2128	227	3158	42	16.8	8.0	3.0
18/3	1964	101	2387	9	13.7	7.9	3.4
20/3	1545	263	2811	25	15.1	7.3	3.7
21/3	2325	285	2999	27	15.5	8.6	5.9
22/3	1917	189	2248	13	13.4	7.7	4.1
23/3	1731	165	2390	8	13.9	7.3	2.0
25/3	1581	323	1976	7	10.7	8.5	7.2
27/3	2534	179	2511	19	12.5	9.6	4.6
28/3	2278	577	2278	36	13.6	8.7	6.4

APPENDIX III

MODEL RESULTS FOR 5/3/79



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